Transmutation Impacts of Generation-IV Nuclear Energy Systems

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Abstract

An assessment of the potential role of Generation IV (Gen-IV) nuclear systems in an advanced fuel cycle has been performed. The focus is on waste reduction and resource utilization. The basic transmutation physics of the Gen-IV systems are compared, illustrating the key differences between thermal and fast spectrum systems. The fuel cycle roles of the reference systems and alternate burner configurations are discussed.

KEYWORDS: Gen-IV, AFCI, fuel cycle, transmutation, transuranics.

1. Introduction

The viability of nuclear energy, in the long term, requires that the issues of waste management, non-proliferation, and uranium supply be adequately addressed. The USDOE Advanced Fuel Cycle Initiative (AFCI) has proposed a logical succession of technologies to evolve the current nuclear fuel cycle enabling the U.S. to actively develop advanced fuel cycle technologies and to effectively contribute worldwide technology choices that will ensure safe, proliferation-resistant nuclear power. [1] The elements of this strategy include the completion of the once-through fuel cycle by opening the federal geologic repository, the application of extended burnup fuels, the development and demonstration of proliferation-resistant fuel cycle technology (possibly incorporating limited recycle in existing reactors), and the development of advanced fast reactors and transition to continuous and sustained spent fuel recycle.

The USDOE also has a program to develop advanced, next-generation nuclear reactors; this program has analogous goals related to safety, sustainability, economics, and proliferation resistance. Six of these advanced designs, called the Generation IV (Gen-IV) nuclear energy systems, have been proposed. [2, 3] The systems include thermal-spectrum designs such as the Very High Temperature Reactor (VHTR), the Supercritical Water-Cooled Reactor (SCWR), and the Molten Salt Reactor (MSR). The Very High Temperature Reactor is the leading candidate in the U.S. Gen-IV Program to develop an inherently safe, economic nuclear system that could produce both electricity and hydrogen with relatively less waste. Three fast-spectrum systems are also being considered: Gas-cooled Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR) and Sodium-cooled Fast Reactor (SFR). The typical system characteristics of the Gen-IV systems are summarized in Table 1; the MSR design is not considered in this study.

Alternate Gen-IV designs (both thermal and fast) have been developed for inclusion in the fuel cycle as dedicated transuranic burners. These burners are intended to address the transuranics (which dominate long-term heat, dose, and radiotoxicity) contained in the large stockpile of spent LWR fuel that has been generated by current U.S. nuclear plants. All of this spent fuel is currently located in prolonged storage at the reactor sites and the total inventory will soon be equal to the original design capacity of the first geologic repository. The general approach in

Table 1: Typical Gen-IV System Characteristics.

Parameter	***VHTR***	***SCWR***	***GFR***	***LFR***	***SFR***
Power, MW_{th}	block: 600-800 Pebble: ~300	~2000-3600	600, 2400	25-400	800-3500
Power Density, W/cm^3	≤ 6.6	≤ 70	100 (50-200)	25-100	200-400
Primary Coolant (T_{Outlet}, ^oC)	He (1000)	SC H_2O (450-500)	He (600-850) SC CO_2	Pb (500-800) Pb-Bi (500-550)	Na (510-550)
Fuel Material	UO_2, $UC_{0.5}O_{1.5}$	UO_2	(U,TRU) carbide, nitride, oxide	(U,TRU) nitride	(U,TRU) oxide, metal alloy
Fuel Form	Triso particle	solid pellet	CerCer dispersion, solid solution, coated particle	solid pellet	pellet or slug
Fuel Element/ Assembly	hex block, pebble	LWR or ACR type pin bundle	hex block, plate, pin, or particle	triangular pitch pin bundle	triangular pitch pin bundle w/duct
Moderator	graphite	water rods(PV) D_2O (PT)	None	None	None
Core Structural Material	graphite	F-M SS, Ni alloy	SiC matrix or cladding, TiN, ODS steel	F-M SS, SiC/SiC composite	ODS ferritic steel

* (T_{Outlet}=coolant outlet temperature; SC=supercritical; ACR=advanced CANDU reactor; CerCer=ceramic-ceramic; F-M=ferretic- martensitic; ODS=oxide dispersion strengthened, PV=pressure vessel; PT=pressure tube)

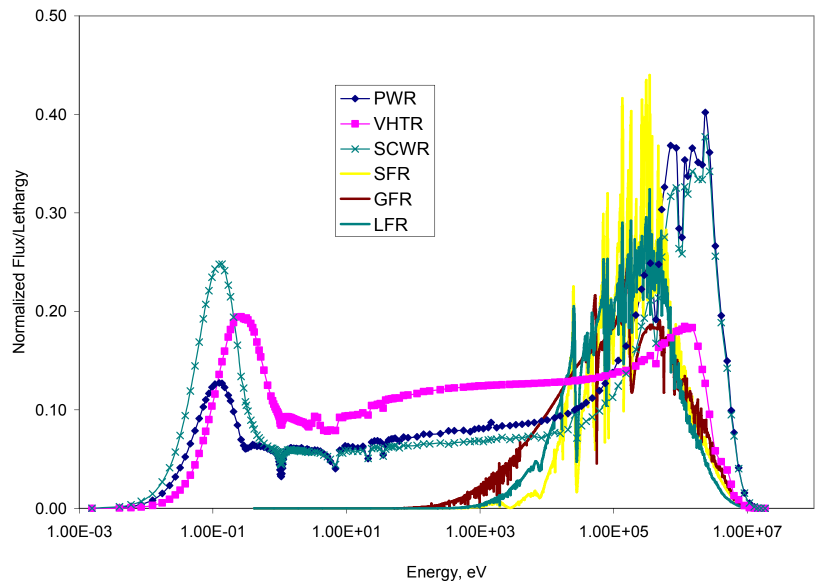
these burner designs is to maximize the fission of transuranics and minimize the production of new transuranics. This can be achieved by using recovered transuranics as the fissile material and removing uranium, to the extent possible. Any fission-based system "burns" transuranics (TRU) at the same rate, ~1 MWt-day per gram fissioned. However, the Gen-IV systems have a wide variety of transmutation characteristics based on spectral differences and design differences (e.g., power density, fuel enrichment, and fuel burnup limits). Burner design modifications can also lead to safety issues for both fast and thermal systems that have to be resolved.

In this paper, we consider the potential role of the Gen-IV concepts in an advanced fuel cycle. The focus is on the waste management and resource utilization goals which are directly impacted by the transmutation performance of the deployed reactors. First, we contrast the basic transmutation physics of the proposed Gen-IV systems in Section 2; key differences between thermal and fast spectrum systems are illustrated. The fuel cycle roles and burner performance of the Gen-IV systems are presented in Section 3. Conclusions are provided in Section 4.

2. Comparison of Transmutation Physics

The basic transmutation physics of the Gen-IV systems have been compared to those of conventional LWRs. In the short term (decades), LWRs will be the dominant reactor type in the world. They are the only existing commercial power reactors in the U.S., with a capacity of ~100 GWe. Similar to conventional LWRs, the Gen-IV VHTR and SCWR designs employ moderators (carbon and supercritical water respectively) to slow down the fission neutrons. Conversely, in the fast spectrum systems moderating materials are avoided. The resulting neutron energy spectra of the Gen-IV systems are compared to that of a PWR in Fig. 1. The nuclear interactions in the PWR/VHTR/SCWR are dominated by the thermal peak around 0.1 eV. The fast spectrum systems have no low energy neutrons, and most neutron reactions occur around the flux peak at 100 keV. Because the transmutation physics of the dominant actinides differs greatly between these two energy ranges (as shown below), thermal/fast energy spectrum is a key distinction with regard to transmutation behavior.

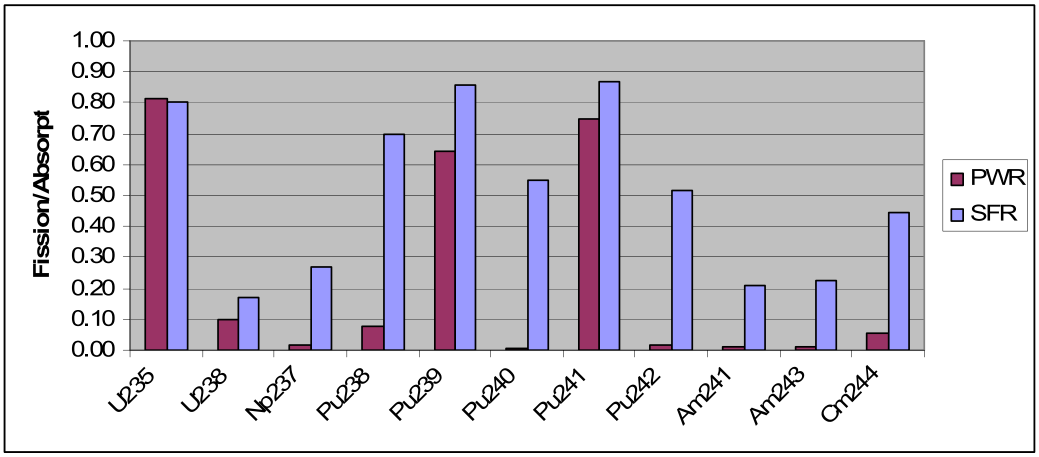
Figure 1: Comparison of Neutron Energy Spectra of Gen-IV Reactors.



The variation of transmutation behavior with energy spectrum is illustrated in Fig. 2; the fission/absorption ratio is compared for dominant actinides in the PWR and SFR spectra. The fission/absorption ratios are consistently higher for the fast spectrum SFR. For fissile isotopes (U-235, Pu-239, and Pu-241) over 80% of fast neutron absorptions result in fission, as compared to 60-80% in the PWR spectrum. In addition, the fast spectrum fission fraction can rise to 50% for fertile isotopes as observed for Pu-240 in Fig. 2, while remaining low (<5%) in a thermal spectrum. Thus, in a fast spectrum, actinides are preferentially fissioned, not transmuted into higher actinides. This implies that fast systems are more "efficient" in destroying actinides because fewer neutrons are lost to capture reactions before eventual fission. Furthermore, the generation rate of higher actinides is significantly reduced at each transmutation step. For example, the Pu-241 content is seven times lower in a sustained fast reactor, compared to a typical LWR; and the higher actinides (americium and curium) continue to build-up with LWR recycle. These higher actinides tend to be more radioactive and can be problematic for fuel handling and fabrication in a closed fuel cycle.

For resource utilization and sustainability goals, it is useful to compare the overall neutron "balance" of the transmutation process; a physics approach for quantification was developed in Ref. 4. The basic idea is to track the neutron balance for transmutation from the source isotope to extinction; fission and (n,2n) reactions produce neutrons while capture reactions consume neutrons. The neutron balance (D-factors) have been compared for the Gen-IV systems; the results allow comparison of the feasibility of transmutation of the different isotopes in each

Figure 2: Comparison of Fission/Absorption Ratio for PWR and SFR.



reactor concept. The D-factors are given in Table 2 for the dominant actinides; note that a positive D-factor indicates net neutron consumption, while a negative D-factor indicates a neutron excess for transmutation of that isotope. As an example, in the case of the Am isotopes, the Am-241 transmutation is a neutron-consuming process in all the thermal concepts, while Am-243 is a slight producer. The fissile isotopes (U-235, Pu-239, and Pu-241) are net producers whatever the spectrum, with more excess neutrons in the fast concepts (e.g., average of about -1.6 for Pu-239).

Significant variations in the D-factor are observed between the concepts. In general, all of the fast reactor systems (harder neutron spectrum) exhibit a significantly more favorable neutron balance compared to the thermal systems. Of particular interest is the neutron balance of U-238 which comprises the bulk of natural uranium resources. The VHTR exhibits a significant neutron defect for U-238 (0.26 net consumption); this is because the fission peak is much less pronounced in the graphite-moderated systems (see Fig. 1) effectively suppressing the direct

Table 2: Comparison of D-Factors for the Gen-IV Concepts.

Isotope	Thermal Concepts			Fast Concepts		
	PWR	VHTR	SCWR	SFR	LFR	GFR
U-235	-0.65	-0.53	-0.70	-1.04	-0.92	-0.84
U-238	-0.02	0.26	0.01	-0.89	-0.71	-0.62
Np-237	0.96	1.11	1.03	-0.88	-0.65	-0.51
Pu-238	0.01	0.12	0.07	-1.50	-1.36	-1.25
Pu-239	-0.83	-0.72	-0.80	-1.71	-1.59	-1.45
Pu-240	0.04	0.12	0.09	-1.28	-1.04	-0.94
Pu-241	-0.95	-0.88	-0.90	-1.42	-1.29	-1.27
Pu-242	0.72	0.79	0.86	-1.12	-0.72	-0.64
Am-241	0.80	0.90	0.88	-0.93	-0.67	-0.58
Am-243	-0.24	-0.20	-0.09	-1.14	-0.85	-0.83
Cm-244	-1.22	-1.19	-1.07	-1.70	-1.53	-1.53

threshold fission of U-238. There is a slight neutron excess in the PWR, although the -0.02 will not overcome parasitic losses which will require roughly 0.38 neutrons. [5] Conversely, the fast reactors have a neutron excess ranging from 0.62 to 0.89. Thus, the fast systems have the potential to efficiently transmute the base U-238 resources, while the thermal systems will require an additional source of neutrons (fissile feed) to drive the transmutation of the U-238.

However, the neutron balance does not completely capture differences in transmutation behavior. For instance, none of the systems can go critical on U-238 alone despite any excess neutrons for complete transmutation. Furthermore, the interim product of thermal U-238 transmutation is reactor-grade plutonium, which can be used as a fissile material (neutron excess) in either type of system. Thus, another key distinction in transmutation behavior is the relative importance of U-238 capture compared to fission transmutation, particularly in the fissile isotopes. For the thermal and fast Gen-IV concepts, the one-group U-238 capture, U-235 fission, and Pu-239 fission cross sections are compared in Table 3. One observes that the fissile fission cross sections are much larger (>25 times) in the thermal systems; while the differences in U-238 capture are only ~5 times. However, the U-238 capture cross section is much larger in the VHTR (compared to the PWR and SCWR) because of its unique spectrum (see Fig. 1); the contributions of epithermal U-238 capture are much more important.

Table 3: Comparison of Key One-group Cross Sections for the Generation-IV Concepts.

Reaction	**Thermal Concepts**			**Fast Concepts**		
	PWR	**VHTR**	**SCWR**	**SFR**	**LFR**	**GFR**
U235f	37.23	44.18	52.80	1.53	1.69	2.09
U238c	0.91	4.80	0.95	0.20	0.26	0.32
Pu239f	89.17	164.54	138.78	1.65	1.69	1.90
U235f/U238c	40.77	9.20	55.75	7.54	6.60	6.59
P239f/U238c	97.66	34.26	146.55	8.14	6.59	6.00

*Notation: U235f and U238c denote one-group U-235 fission and U-238 capture cross sections, respectively.

Because U-238 capture is relatively more likely in a fast system this promotes their use as U-238 converters. However, this difference also implies that the fast systems will need a much higher enrichment to overcome the U-238 capture; compare the Pu239f/U-238c ratio of ~100 for a PWR, as compared to ~7 for the fast systems. Therefore, despite the inferior neutron balance for the individual isotopes (see Table 2), reactions in the fissile isotopes are favored in the thermal energy range. Therefore, the thermal spectrum system can operate on much lower enrichment because of the low relative probability of U-238 capture.

Based on these differences in transmutation physics, the Gen-IV thermal concepts have been configured for low enriched uranium (LEU) fuel utilization in a once-through fuel cycle. For this approach, waste management is improved by increased burnup (provide more energy from a given fuel mass) and improved thermal efficiency (more electrical power for a given energy production). In contrast, the base Gen-IV fast concepts are configured for U-238 utilization, the fissile material is recycled transuranics (TRU) and high in-core conversion rate is exploited to extend resources. For this approach, waste management is improved by increased burnup (more energy each recycle pass), improved thermal efficiency, and limited recycle losses.

3. Role of Gen-IV Systems in an Advanced Fuel Cycle

The Gen-IV systems are being developed to provide a long-term, sustainable fuel supply for the expanded use of nuclear energy. As stated in the Gen-IV implementation strategy, two research priorities are being pursued: [6]

1. "*Mid Term Priority: Develop a Next Generation Nuclear Plant to achieve economically competitive energy products, including electricity and hydrogen*." This system is needed to meet growing energy demand and maintain the share of nuclear energy in the United States.
2. "*Long-Term Priority: Develop a fast reactor to achieve significant advances in proliferation resistance and sustainability*." In this phase, the waste management and resource utilization gains are emphasized. Thus, the base Gen-IV systems are intended as a future replacement of existing plants for electricity production, and advanced technology for expanded nuclear energy production.

For the <u>electricity production mission</u>, the base Gen-IV systems offer a variety of fuel cycle options. Similar to advanced LWRs, the VHTR and SCWR concepts continue a once-through fuel cycle based on low enriched uranium (LEU) fuels. [3] The Gen-IV systems however provide improved thermal efficiency (by higher temperature operation), and higher fuel burnup, and thus give some improvement in the waste generation and resource utilization of the fuel cycle. For low uranium prices and cheap direct disposal space, current reactors demonstrate that the once-through fuel cycle is economical. The base Gen-IV fast systems (SFR, GFR, and LFR) operate in a closed fuel cycle using recovered transuranics (TRU) and uranium. These systems also provide improved thermal efficiency and higher fuel burnup. The application of continuous recycle provides large improvements in the waste generation and resource utilization of the fuel cycle; for example, the TRU waste/energy is reduced by a factor of 100, and depleted uranium can be utilized to extend resources. These benefits require fuel reprocessing and re-fabrication to recycle TRU materials. Thus, the decision to transition to this fuel cycle will be impacted by the future availability/cost of waste disposal space and uranium resources.

Another aspect of the Gen-IV approach is to expand nuclear power to alternative energy needs such as process heat, hydrogen production, and/or water desalination. High temperature operation is expected to improve application for these alternate energy missions. The VHTR and GFR concepts can achieve very high temperatures (>850^{o}C) which are targeted for chemical cycles for hydrogen production. [3] Although the other concepts have higher outlet temperatures than current LWRs, their temperature range of (500-600^{o}C) would require lower temperature hydrogen production technology. Thus, evolution of hydrogen production and alternate energy technologies must also be considered.

Advanced reactor technologies are also being considered in the AFCI for a <u>waste management mission</u>. Continuation of the current once-through fuel cycle would produce several hundred thousand metric tons of spent fuel this century; thus, nuclear waste disposal solutions will be required for sustained nuclear power. As an alternative to vastly expanded permanent disposal space, the AFCI is investigating recycle technologies that avoid direct disposal of the spent fuel; in particular, the TRUs are removed from the spent fuel (reducing the long-term heat, dose, and radiotoxicity) and recycled in advanced reactors for consumption. The Gen-IV systems can be modified to burner designs for this purpose.

In burner mode, the Gen-IV systems could be deployed to manage the TRU production of a sustained fleet of once-through LWRs; this strategy allows a gradual transition into advanced fuel cycle and reactor technology. At discharge, commercial LWR spent fuel (50 GWd/MT) contains 5.3 weight% fission products compared to a transuranic (TRU) content of 1.4%. Thus, for a sustained equilibrium with the existing LWRs a complementary pure burner system must comprise 1.4/5.3 ~ 25% the thermal power capacity of the LWR enterprise that is being supported. When fertile fuel is utilized, additional TRUs are created requiring additional fissions for their destruction; this results in higher capacity for the transmutation sector. For the Gen-IV burner concepts, the impacts of conversion ratio and thermal efficiency on the required power fraction are noted in Table 4.

Table 4: Comparison of Gen-IV Burner Requirements.

System	Thermal		Fast					
	PWR	VHTR	SFR			GFR		LFR
Conversion Ratio		0.00	0.50	0.25	0.00	0.24	0.00	0.25
TRU Production Rate, g/MWtd	0.25	-1.01	-0.47	-0.74	-0.99	-0.76	-1.04	-0.75
Thermal Power Ratio, % of PWR		25	53	34	25	33	24	33
Thermal Efficiency, %	33	47.7	38-42	38-42	38-42	45	45	43
Electrical Power Ratio, % of PWR		36	61-68	39-43	29-32	45	33	43

As aforementioned, all the pure burners (CR=0) require a thermal power of 25% the LWR capacity to completely consume the LWR TRU production. At higher conversion ratio, more burners are needed with the power fraction increasing to 53% (0.53 MWt of burner needed for every 1 MWt of LWR power) at CR=0.5. Because the Gen-IV systems have higher thermal efficiency than conventional PWRs, the electrical power ratio is slightly higher than the thermal power ratio, with the burner fraction ranging from 29-36% for pure burners. This would imply that the burners are providing ~25% of the total nuclear electricity. Thus, a significant infrastructure of burners will be required to manage TRUs that would be generated by sustained operation of once-through LWRs.

Because of its high thermal efficiency and non-uranium fuel form the VHTR has the highest electrical power ratio of the pure burners in Table 4. However, it may be difficult to completely destroy the TRU in this concept. Transuranics recycle in thermal systems may be constrained by neutron balance, higher actinide build-up, or safety impact of high TRU content fuels. Current studies show that ~60% burnup can be obtained in a single pass VHTR. [7] A single-pass application would reduce the power fraction to 22%, but nearly half the TRUs still remain in the waste, and the repository benefits (loading, dose, etc.) are limited to roughly a factor of 2.

Conversely, the Gen-IV fast reactor (FR) systems are designed to operate on TRU-based fuels with continuous recycle. The key limitation to achieving low conversion ratio is the desire to utilize conventional fuel enrichments: for perspective, CR=0.5 can be obtained at 30% enrichment (demonstrated fuels), CR=0.25 at 50% enrichment, and CR=0 at 100% TRU enrichment. As shown in Table 4, the FR power fraction varies from 53% at CR=0.5 to 34% at CR=0.25 to 25% as a pure burner.

Table 5: Comparison of Gen-IV Fast Burner Performance (CR=0.25 Designs).

System	SFR	GFR	LFR
Net TRU Destruction, g/MWt-day	0.74	0.76	0.75
System Power, MWt	840	600	840
Outlet Temperature, oC	510	850	560
Thermal Efficiency, %	38	45	43
Power Density, W/cc	300	103	77
TRU Inventory, kg	2250	3420	4078
Fuel Volume Fraction, %	22	10	12
TRU Enrichment, % TRU/HM	44 - 56	57	46 - 59
Fuel Burnup, GWd/t	177	221	180

Because the transmutation physics behavior is similar for the fast burner concepts (see Section 2), a similar design approach was employed to achieve low conversion ratio for SFR, GFR and LFR concepts; by reducing the fuel volume fraction, fertile material was removed. For a given conversion ratio, the TRU destruction rate and compositions are very similar. However, variations in other fuel cycle performance parameters are observed because of design differences as shown in Table 5. In particular, the power density of the SFR is much higher; the GFR requires low power density for safe decay heat removal, while the LFR requires low power density for slow coolant flow rates. The compact SFR approach has some economic benefits; although higher thermal efficiency and design simplifications (e.g., removal of secondary loop) are being pursued for GFR and LFR. Another impact of the low power density is a higher TRU inventory (by roughly a factor of 2 per MWt). Low power density implies a reduced fractional consumption rate (% of inventory/year) for the burner and significantly more LWR TRU would be needed to startup the lower power density options. The burners have a similar discharge burnup despite these inventory differences.

Another refinement investigated is to utilize a double-tier transmutation system to further reduce the burner fraction. The primary goal of the transmutation mission remains – to transmute the hazardous components of spent nuclear fuel. Thus, the majority of the transuranic (TRU) material needs to be fissioned, producing ~1 MW-day of energy for every gram. However, other systems may be more efficient in consuming this material, particularly early in the process when the fissile content is still high. Thus, a variety of alternative fuel cycle strategies have been proposed where the transmutation campaign is divided into several phases, denoted tiers. For example, the TRU material could first be irradiated in a thermal reactor (to burn the plutonium) with subsequent irradiation in a fast spectrum system (to burn the minor actinides).

If the initial irradiation is conducted in a thermal spectrum system, the fissile materials will be preferentially consumed. Furthermore, as discussed in Section 2, significant quantities of higher actinides (americium and curium) may be generated, particularly with deep burnup. Thus, the feed material for the Tier 2 fast spectrum system is less reactive but highly radioactive; and the final destruction of the radiotoxic minor actinides is more difficult. The significant change in feed isotopics impacts the performance of the fast burner system. The reduced fissile content of the heavy metal requires a significant increase in the TRU inventory and results in a significant reduction in the burnup (in some case by 25%). Because the systems exhibit similar discharge fluence levels, this reduced burnup cannot be recouped by increasing the fuel residence time. On the other hand, the decreased fissile content (more fertile material) results in lower burnup reactivity loss rates.

Overall, the AFCI multi-tier studies indicate that the utilization of a first tier thermal spectrum system can significantly reduce the power capacity requirements for complementary fast burners. For example, if 50% of the TRU (i.e., the majority of the plutonium) can be destroyed in a first tier burner; the power fractions in Table 4 would be cut in half. However, even in the double tier scenarios, the burner capacity requirements remain significant (maybe as low as 10% the total nuclear generating capacity), indicating that a significant transition to Gen-IV burner reactors will be required to achieve the transmutation goals.

4. Conclusions

The potential role of Gen-IV nuclear systems in an advanced fuel cycle has been evaluated in this study. The Gen-IV systems considered are the thermal-spectrum VHTR and SCWR, and the fast-spectrum GFR, LFR, and SFR. The study evaluated the impact of each system on advanced fuel cycle goals, particularly related to waste management and resource utilization. The transmutation impact of each system was also assessed, along with variant designs for TRU burning.

It was shown that the fast-spectrum systems have a consistently higher fission/absorption ratio, indicating that actinides are preferentially fissioned and not transmuted into higher actinides. This implies that fast systems are more "efficient" in destroying actinides because fewer neutrons are lost to capture reactions before eventual fission. Additionally, the generation of higher actinides is suppressed. The fast-spectrum systems were also shown to give a more favorable neutron balance that allows the efficient transmutation of U-238, allowing extension of uranium resources. Conversely, the thermal system would require an additional source of neutrons (fissile feed) to drive the transmutation of the U-238. These core physics characteristics have direct correlations to the base core designs and fuel cycle strategies of the thermal- and fast-spectrum Gen-IV systems.

The base fuel cycle for the thermal reactor concepts (VHTR and SCWR) is a once-through fuel cycle using low-enriched uranium fuels. The higher burnup and thermal efficiency of the VHTR gives an advantage in terms of heavy-metal waste mass and volume, with lower decay heat and radiotoxicity of the spent fuel per energy produced, compared to a PWR. Fuel utilization might, however, be worse compared to the PWR, because of the higher fuel enrichment essential to meeting the VHTR system design requirements. The SCWR concept also featured improved thermal efficiency; however, benefits are reduced by the lower fuel burnup.

The base fuel cycle for the fast reactor concepts (SFR, GFR, and LFR) is a closed fuel cycle using recycled TRU and depleted uranium fuels. Waste management gains from complete recycle are substantial, with the final disposition heat load determined by processing losses. The base Gen-IV concepts allow consumption of U-238 significantly extending uranium resources (up to 100 times). These benefits come at the cost of fuel reprocessing and fuel re-fabrication with recycled TRU. Thus, the decision to transition to this closed fuel cycle will depend on future availability of waste disposal space and uranium resources.

For both thermal and fast concepts, recent design studies have pursued the development of dedicated burner designs. An evaluation of these studies indicated that a burnup of 50-60% might be possible in a VHTR burner design using non-uranium (transuranics) fuel. However, practical limits related to higher actinide buildup and safety impact may limit the extent of TRU burning in thermal reactors.

Fast burner designs have been developed for both conventional and high TRU content fuel forms. In general, the conversion ratio can be varied within a system by changing the uranium loading. Similar transmutation performance has been shown for the SFR, GFR, and LFR concepts; however, some design features (e.g., long-lived core) need to be avoided to attain significant material consumption in a burner configuration.

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